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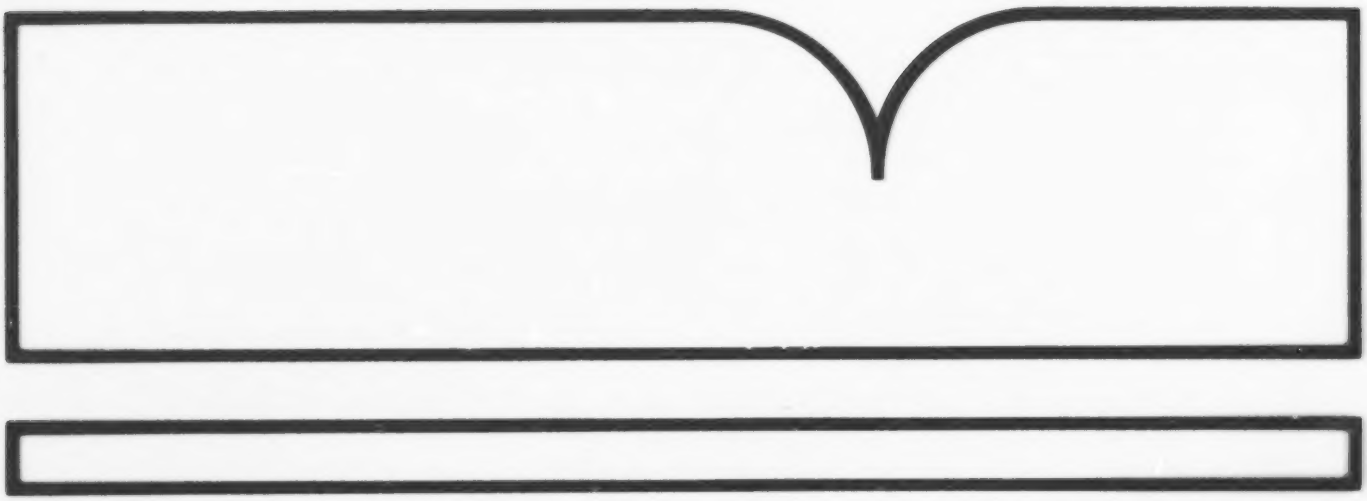

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16. ABSTRACT

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The UV/oxidation technology uses UV radiation, ozone, and hydrogen peroxide to oxidize organic contaminants present in water. At the LB&D site, this technology was evaluated in treating ground water contaminated with volatile organic compounds (VOCs). The Ultrox system achieved VOC removals greater than 90 percent. The majority of VOCs were removed through chemical oxidation. However, for a few VOCs, such as 1,1,1-trichloroethane (1,1,1-TCA) and 1,1-dichloroethane (1,1-DCA) stripping also contributed toward removal. The treated ground water met the applicable discharge standards (NPDES) for disposal into Coyote Creek at 90 percent confidence level. There were no harmful air emissions from the Ultrox system into the atmosphere.

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A Field Evaluation of the UV/Oxidation Technology To Treat Contaminated Groundwater

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ABSTRACT

This paper presents the field evaluation results of the ultraviolet radiation (UV)/oxidation technology developed by Ultrox International, Santa Ana, California. The field evaluation of the technology was performed at the Lorentz Barrel and Drum (LB&D) site in San Jose, California, under the Superfund Innovative Technology Evaluation (SITE) program from Feb. 27 through Mar. 10, 1989.

The UV/oxidation technology uses UV radiation, ozone and hydrogen peroxide to oxidize organic contaminants present in water. At the LB&D site, this technology was evaluated in treating groundwater contaminated with volatile organic compounds (VOCs). The Ultrox system achieved VOC removals greater than 90%, and the majority of VOCs were removed through chemical oxidation. However, for a few VOCs, such as 1,1,1-trichloromethane (1,1,1-TCA), and 1,1-dichloroethane (1,1-DCA) stripping also contributed toward removal. The treated groundwater met the applicable discharge standards (NPDES) for disposal into a local waterway at 95% confidence level. There were no harmful air emissions from the Ultrox system into the atmosphere.

INTRODUCTION

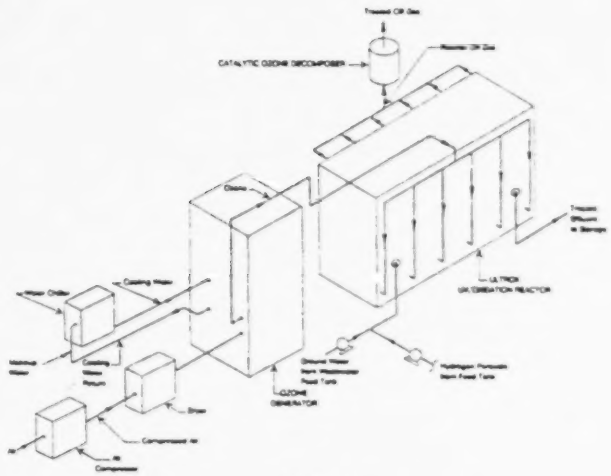
The EPA is finding better solutions to hazardous waste remediation through its Superfund Innovative Technology Evaluation (SITE) program. The SITE program was created to demonstrate and evaluate technologies that may destroy or permanently change the composition of hazardous waste in the environment by significantly reducing the waste's toxicity, mobility or volume. The SITE program also generates reliable performance and cost data for these treatment technologies to be used in evaluating alternatives under the Superfund site remediation process.

In 1988, Ultrox International's proposal for its ultraviolet radiation (UV)/oxidation technology was selected by U.S. EPA's Office of Research and Development (ORD) and Office of Solid Waste and Emergency Response (OSWER) under the SITE program. This technology was demonstrated at the Lorentz Barrel and Drum (LB^3D) site in San Jose, California, through a cooperative effort between Ultrox International, ORD, OSWER and U.S. EPA Region IX.

UV/OXIDATION TECHNOLOGY: EQUIPMENT AND PROCESS DESCRIPTION

The Ultrox UV/oxidation treatment system uses UV radiation, ozone and hydrogen peroxide to oxidize organics in water. The major components of the Ultrox system are the UV/oxidation reactor module, air compressor/ozone generator module, hydrogen peroxide feed system and catalytic ozone decomposition (Decompozon) unit. An isometric view of the Ultrox system is shown in Figure 1.

The UV/oxidation reactor used in the demonstration (Model PM-150) has a volume of 150 gal and is 3 ft long by 1.5 ft wide by 5.5 ft high. The reactor is divided by five vertical baffles into six chambers and contains 24 UV lamps (65 w each) in quartz sheaths. The UV lamps are installed vertically and are evenly distributed throughout the reactor (four lamps per chamber). Each chamber also has one stainless steel sparger that extends along the width of the reactor. These spargers uniformly diffuse ozone gas from the base of the reactor into the water. Hydrogen peroxide is introduced in the influent line to the reactor from a storage tank. An in-line static mixer is used to disperse the hydrogen peroxide into the contaminated water in the influent feed line.


CATALYTIC OZONE DECOMPOSER
Ozone
Ozone Vent
Ozone Sparger
Ozone Sparger
Ozone Sparger

are known to react with organics more rapidly than the oxidants ozone, hydrogen peroxide and UV radiation. They are also much less selective in oxidation reactions than the three oxidants. Ozone that is not transferred to the contaminated water will be present in the reactor off-gas. This ozone is subsequently destroyed by the Decompozon unit before being vented to the atmosphere. The treated water flows from the reactor for appropriate disposal.

LB&D SITE HISTORY

The LB&D site is in San Jose, Santa Clara County, California. This site was used for drum recycling operations from about 1947 to 1987. The drums contained residual aqueous wastes, organic solvents, acids, metal oxides and oils. A preliminary site assessment report for the LB&D site showed that the groundwater and soil were contaminated with organics and metals[1]. In 1987, the LB&D facility ceased operation due to a restraining order issued by the California Department of Health Services. U.S. EPA Region IX assumed the responsibility for site remediation.

The shallow groundwater at the LB&D site was selected as the waste stream for evaluating the UV/oxidation technology. Groundwater samples collected in December, 1988, indicated that several volatile organic compounds (VOCs) were present in the shallow aquifer. VOCs detected at high levels included trichloroethylene (280 to 920 μ/L), vinyl chloride (51 to 146 μ/L) and 1,2-trans-dichloroethylene (42 to 68 μ/L). The pH and alkalinity of the groundwater were approximately 7.2 and 600 mg/L as $CaCO_3$, respectively. These measurements indicated that bicarbonate ion (HCO_3), which acts as an oxidant scavenger, was present at high levels. Other oxidant scavengers such as bromide, cyanide and sulfide were not detected.

TECHNOLOGY DEMONSTRATION

The objectives of the technology demonstration were to: (1) evaluate the ability of the Ultrox system to treat VOCs present in the groundwater at the LB&D site at different operating conditions; (2) determine the extent of VOC stripping, if any, from the bubbling of ozone gas; (3) evaluate the efficiency of the Decompozon unit to decompose reactor off-gas ozone; (4) determine the operating conditions needed for the effluent to meet applicable discharge standards (NPDES) for disposal into a nearby waterway; and (5) develop the information required to estimate operating costs for the treatment system, such as electricity consumption and oxidant doses.

Testing Approach

Eleven test runs were performed to evaluate the Ultrox system under various operating conditions. After these runs, two additional runs were performed to determine if the system's performance was reproducible. The operating conditions for the runs are summarized in Table 1. All 13 runs were performed over a period of 2 wk.

The study was designed to evaluate the Ultrox system by adjusting the levels of five operating parameters: (1) influent pH, (2) retention time, (3) ozone dose, (4) hydrogen peroxide dose and (5) UV radiation intensity. The initial operating conditions (Run 1), given in Table 1, were based on the treatability study conducted by Ultrox on LB&D site groundwater.

During the demonstration, a preliminary estimate of the Ultrox system's performance in each run was obtained based on the effluent concentrations of three indicator VOCs. The VOCs selected for this purpose were trichloroethylene (TCE, a major volatile contaminant at the site), 1,1-dichloroethane (1,1-DCA) and 1,1,1-trichloromethane (1,1,1-TCA). 1,1-DCA and 1,1,1-TCA were selected because Ultrox's experience indicated that these VOCs are relatively difficult to oxidize.

In the first three runs, the influent pH was adjusted by adding sulfuric acid to evaluate the system's performance and to determine the "preferred" influent pH ["preferred" operating conditions are those conditions in which: (1) effluent concentrations of indicator VOCs are below NPDES limits and (2) the relative operating costs are the lowest]. Once the "preferred" influent pH was determined, it remained at that level for the remaining runs. The Ultrox system performance was then studied by varying other parameters, one at a time, as shown in Table 1,

Table 1
Operating Parameters Matrix for the Ultrox System Demonstration

Run No.	Retention Time	Ozone Dose	H_2O_2 Dose	UV Lamps	Influent pH
1	X*	Y*	Z*	All ON	Unadjusted
2	X	Y	Z	All ON	(Unadjusted - 1)
3	X	Y	Z	All ON	(Unadjusted - 2)
4	1.5X	Y	Z	All ON	Preferred*
5	0.5X	Y	Z	All ON	Preferred
6	Preferred	1.5Y	Z	All ON	Preferred
7	Preferred	0.5Y	Z	All ON	Preferred
8	Preferred	Preferred	1.5Z	All ON	Preferred
9	Preferred	Preferred	0.5Z	All ON	Preferred
10	Preferred	Preferred	Preferred	Only ON in the first three chambers	Preferred
11	Preferred	Preferred	Preferred	Only ON in the last three chambers	Preferred
12*	Preferred	Preferred	Preferred	Preferred	Preferred
13*	Preferred	Preferred	Preferred	Preferred	Preferred

Notes:

* X = 40 minutes.

* Y = 75 mg/L.

* Z = 25 mg/L.
(X, Y, and Z values were determined by Ultrox International to be the optimum conditions for treating ground water in the treatability study at the LB&D site.)

* "Preferred" operating conditions are those conditions in which (1) the concentrations of effluent indicator VOCs are below their respective NPDES limits and (2) the relative operating costs are the lowest.

* Verification runs performed to check the reproducibility of the Ultrox system's performance at the "preferred" operating conditions.

to determine the "preferred" values for those parameters. The criteria were the same as those used in determining the "preferred" value for the influent pH. After the "preferred" values were determined for all five operating parameters, two runs (12 and 13) were performed to verify the reproducibility of the Ultrox system's performance at the "preferred" operating conditions. By duplicating the "preferred" operating conditions determined during the previous 11 runs, the two verification runs served to ensure that the results could be based on repeated observations, with comparable findings.

Sampling and Analytical Procedures

Air and water samples were collected from the Ultrox system at the locations shown in Figure 2. For the critical parameters in this study (VOCs in water), six replicate samples were collected. Duplicate samples were collected for other parameters listed in Table 2. Sampling at the influent port began approximately 15 min after each run was started. At other locations in the reactor, sampling began after three retention times to allow the system to reach steady-state. All the air and water samples for off-site laboratory analysis were preserved as required before being shipped to the laboratory.

The analytical methods followed in this study are listed in Table 2. To obtain reliable data, strict QA/QC procedures were followed. Details on all aspects of the QA/QC procedures are presented in the Demonstration Plan and the Technology Evaluation Report[2,3].

RESULTS AND DISCUSSION

This section summarizes the results of the Ultrox system demonstration and also presents an evaluation of the UV/oxidation technology's effectiveness in removing VOCs from the groundwater at the LB&D site.

Summary of Results for VOCs

The purpose of the test runs was to evaluate the effectiveness of the Ultrox system in removing 44 VOCs present in the groundwater at the LB&D site. The removal efficiencies and concentration profiles of all VOCs are not presented in this paper. Instead, a summary of the results is given.

The mean concentration profiles and the discharge standards (NPDES) for the three indicator contaminants (TCE 1,1-DCA and 1,1,1-TCA) in

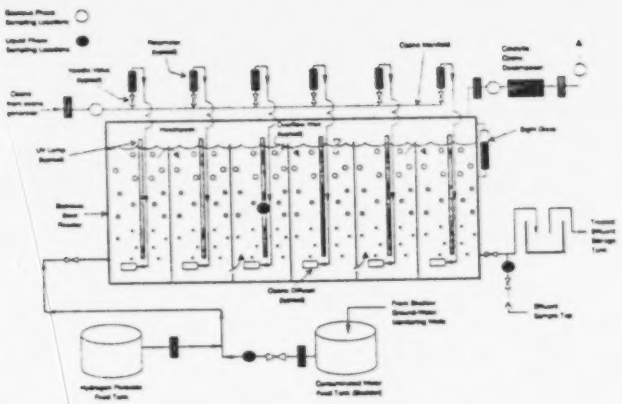


Figure 2
Ultrox System Sampling Locations

each run for each sampling location are plotted in Figures 3, 4 and 5. The VOC concentrations progressively decreased from the influent to the mid-point and from the mid-point to the effluent except for Run 3. In Run 3, the concentration of 1,1-DCA at mid-point was higher than that in the influent. It is believed that either the mid-point concentration or the influent concentration is just an outlier. This progressive decrease in containment concentration is due to the ozone and the UV radiation provided in the last three chambers (after the mid-point) and the increase in the retention time from the mid-point to the effluent port. Additionally, the effluent and mid-point VOC concentrations are comparatively high in Run 7, which appears to be due to the decreased ozone dose during that particular run.

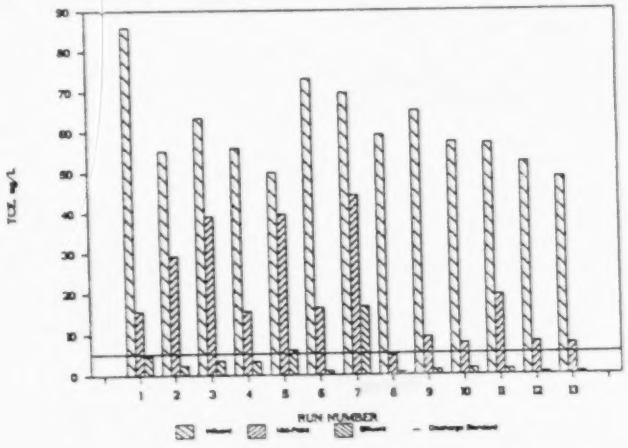


Figure 3
TCE Concentrations in Different Runs

The average effluent concentrations (determined during the demonstration by analyzing only two of the six replicates) for each indicator VOC with the discharge standard (NPDES) showed that the effluent met the discharge limits in Runs 8 and 9. Since a lower hydrogen peroxide dose was used in Run 9, compared to Run 8, Run 9 was chosen as the "preferred" operating run. However, based on a complete analysis of the six replicates performed after the demonstration, the mean concentration of 1,1-DCA was found to be slightly higher than 5 μ/L, the discharge standard for the VOC. Since Run 9 had the "preferred" operating conditions during the demonstration, the verification runs (12 and 13) were performed at those conditions.

A comparison of 95% upper confidence limit (UCL) values for the effluent VOCs in Runs 9, 12 and 13 with the discharge standards (NPDES) is presented in Table 3. The UCL values were calculated using

Table 2
Analytical Methods

Analyte	Matrix	Method Type	Method Reference
Alkalinity	Liquid	Field	MCAWW 310.1[a]
Arsenic	Liquid	Lab	SW-846 7060[c]
BNA (Semivolatiles)	Liquid	Lab	SW-846 8270[c]
Chromium (Cr^{+6})	Liquid	Lab	SW-846 7195[c]
Chloride	Liquid	Lab	SM 429[b]
Chromium	Liquid	Lab	SW-846 7191[c]
Conductivity	Liquid	Field	Manual[d]
Hydrogen Peroxide	Liquid	Field	Boltz et al. (1979)[e]
Metals (Barium, Cobalt, Iron, Manganese, Nickel, Zinc, Potassium, Calcium, Magnesium, and Sodium)	Liquid	Lab	SW-846 6010[c]
Ozone	Liquid	Field	Bader and Hoigne(1982)[f]
Ozone	Air	Field	40 CFR Part 50[g]
pH	Liquid	Field	Manual[d]
Pesticides/PCBs	Liquid	Lab	SW-846 8080[c]
Silica	Liquid	Lab	SW-846 6010[c]
Sulfate	Liquid	Lab	SM 429[b]
Temperature	Liquid	Field	Manual[d]
Total Organic Carbon	Liquid	Lab	SM 505A[b]
Turbidity	Liquid	Field	Manual[d]
Volatile Organics	Liquid	Lab	SW-846 8010 and 8020[c]
Volatile Organics	Liquid	Lab	SW-846 8240[c]
Volatile Organics:			
Vinyl Chloride	Air	Lab	NIOSH 1007[h]
1,1-Dichloroethene	Air	Lab	NIOSH 1015[h]
1,1-Dichloroethane	Air	Lab	NIOSH 1003[h]
1,2-Dichloroethene	Air	Lab	NIOSH 1003[h]
1,1,1-Trichloroethane	Air	Lab	NIOSH 1003[h]
Trichloroethene	Air	Lab	NIOSH 1022[h]
Benzene	Air	Lab	NIOSH 1500[h]
1,1,2,2-Tetrachloroethane	Air	Lab	NIOSH 1019[h]
Acetone	Air	Lab	NIOSH 1300[h]

the one-tailed Student's t-test. Table 3 shows that the effluent met the discharge standards for all regulated VOCs at the 95% confidence level in Runs 12 and 13. In Run 9, the mean concentrations for 1,1-DCA and 1,2-DCA exceeded the discharge standards. Although 1,1-DCA and 1,2-DCA were present at levels slightly greater than the discharge standards, the difference in performance among the three runs is negligible.

The mean concentration profiles for total VOCs are given in Figure 6. A comparison of the VOC concentrations presented in Figure 6 with those in Figures 3, 4 and 5 indicates that the concentration profiles for total VOCs are similar to those for the indicator VOCs. For example, the peaks present at the mid-point and effluent for indicator VOCs are also present in the total VOC concentration profiles.

The percent removals for the indicator VOCs and total VOCs are presented in Figure 7. The figure shows that the removal efficiencies

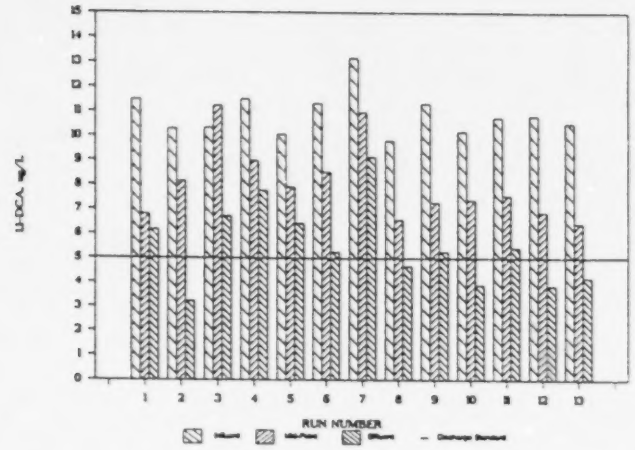


Figure 4
1,1-DCA Concentrations in Different Runs

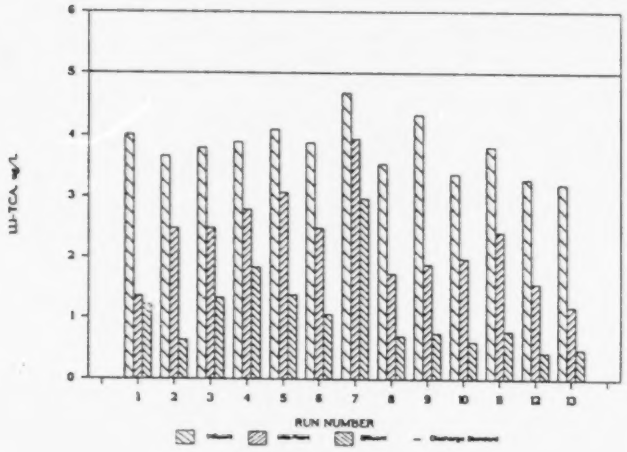


Figure 5
1,1,1-TCA Concentrations in Different Runs

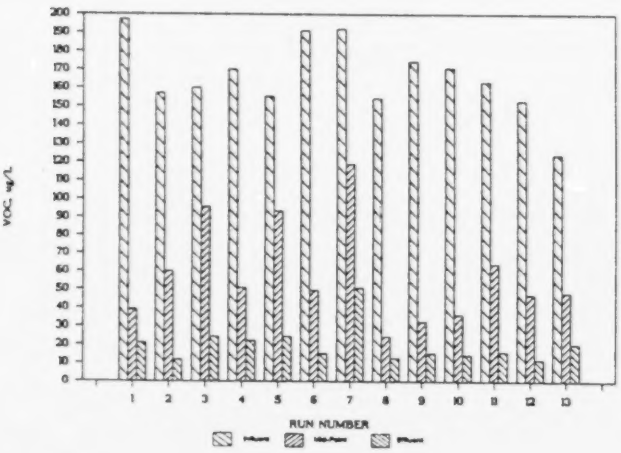


Figure 6
Total VOC Concentrations in Different Runs

Table 3
Comparison of Effluent VOC Concentrations in Runs 9, 12 and 13

	Mean, µg/L	95% UCL, µg/L	RT, µg/L	Conclusion
Run number: 9				
1,1,1-TCA	0.75	1.0	5	OK
1,1,2,2-PCA	0.045	0.045	5	OK
1,1-DCA	5.3	5.5	5	N
1,1-DCE	0.000	0.000	5	OK
1,2-DCA	1.3	1.4	1	N
1,2-DCPA	3.3	3.4	5	OK
Benzene	0.023	0.026	5	OK
Chloroethane	0.000	0.000	5	OK
Chloroform	1.1	1.2	5	OK
PCE	0.24	0.63	5	OK
T-1,2-DCE	0.000	0.000	5	OK
TCE	1.2	1.3	5	OK
Vinyl Chloride	0.11	0.11	2	OK
Run number: 12				
1,1,1-TCA	0.43	0.48	5	OK
1,1,2,2-PCA	0.045	0.045	5	OK
1,1-DCA	3.8	4.2	5	OK
1,1-DCE	0.000	0.000	5	OK
1,2-DCA	0.92	1.0	1	OK
1,2-DCPA	2.6	2.9	5	OK
Benzene	0.023	0.026	5	OK
Chloroethane	0.000	0.000	5	OK
Chloroform	0.74	0.82	5	OK
PCE	0.19	0.38	5	OK
T-1,2-DCE	0.000	0.000	5	OK
TCE	0.55	0.65	5	OK
Vinyl Chloride	0.11	0.11	2	OK
Run number: 13				
1,1,1-TCA	0.48	0.54	5	OK
1,1,2,2-PCA	0.045	0.045	5	OK
1,1-DCA	4.2	4.5	5	OK
1,1-DCE	0.000	0.000	5	OK
1,2-DCA	1.0	1.0	1	OK
1,2-DCPA	2.9	3.1	5	OK
Benzene	0.45	0.52	5	OK
Chloroethane	0.000	0.000	5	OK
Chloroform	0.81	0.87	5	OK
PCE	0.091	0.17	5	OK
T-1,2-DCE	0.000	0.000	5	OK
TCE	0.63	0.73	5	OK
Vinyl Chloride	0.12	0.12	2	OK

Notes:

95% UCL: Upper 95% Confidence Limit
RT: Regulatory Threshold
OK: Effluent met the regulatory threshold
N: Effluent did not meet the regulatory threshold

Abbreviations:
1,1,1-TCA: 1,1,1-Trichloroethane; 1,1,2,2-PCA: 1,1,2,2-Tetrachloroethane; 1,1-DCA: 1,1,-Dichloroethane; 1,1-DCE: 1,1-Dichloroethylene; 1,2-DCA: 1,2-Dichloroethane; 1,2-DCPA: 1,2-Dichloropropane; PCE: Tetrachloroethylene; T-1,2-DCE: Trans-1,2-Dichloroethylene; TCE: Trichloroethylene.

for TCE were higher than those for 1,1-DCA and 1,1,1-TCA which is consistent with the rationale used in selecting the indicator VOCs. The percent removals for total VOCs and the indicator VOCs decreased considerably in Run 7, which appears to be due to the decreased ozone dose.

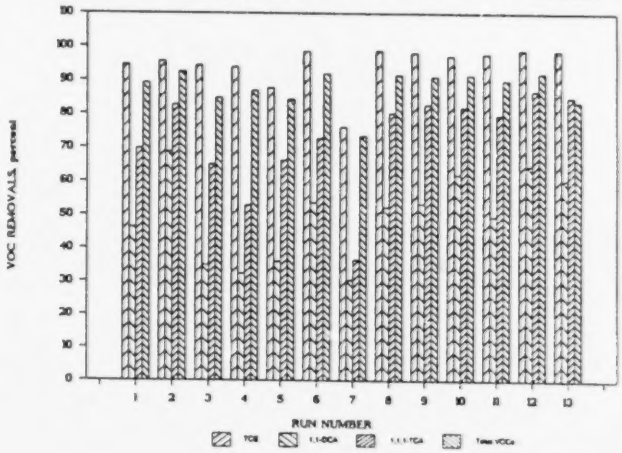


Figure 7
VOC Removals in Different Runs

Since ozone gas is bubbled through the groundwater treated by the Ultrox system, the VOC removal could be attributed to stripping in addition to oxidation. To determine the extent of stripping within the treatment system, VOC samples were collected from the reactor off-gas. Twenty-five samples were collected during the demonstration. Although 1,1-DCE, 1,2-DCE, benzene, 1,1,2,2-tetrachloroethane and acetone were present in two samples at concentrations close to the detection limits, TCE, vinyl chloride, 1,1,1-TCA and 1,1-DCA were detected more frequently. To determine the extent of stripping, the emission rates in the reactor off-gas for these latter four VOCs were compared to the VOC removal rates (estimated by difference between the VOC input rates at the influent and output rates at the effluent ports of the Ultrox system). The results are summarized in Table 4.

Table 4
Extant of VOC Stripping in the Ultrox System

Run No.	Air flow rate / Water flow rate	Percent Stripping Contribution For 1,1-DCA 0.0043[b]	TCE 0.0091[b]	1,1,1-TCA 0.014[b]	VC[a] 0.082[b]
1	2.1	7.4	2.0	43	0.013
2	2.3	9.1	3.4	34	0.95
3	2.1	9.9	2.7	31	0.013
4	2.0	7.4	3.0	29	0.01
5	2.1	17	3.5	29	1.7
6	4.5	16	1.2	65	0.072
7	1.0	4.9	1.2	12	3.1
8	4.5	23	7.5	85	1.2
9	4.5	16	6.6	58	0.04
10	4.3	27	9.4	73	1.1
11	4.6	44	24	>99	13
12	4.4	34	7.0	76	8.9
13	4.3	37	26	75	1.8

Notes:

a VC: Vinyl Chloride

b Henry's law constant of the VOC, atm-m³/mol.

Since the extent of stripping for any particular VOC is expected to be proportional to the ratio of the air flow rate to the water flow rate, this ratio is presented in the table. The ratio for Runs 1 to 5 is approximately 2; for Run 6 and Runs 8 to 13, it is approximately 4.5; and for Run 7, it is 1. If stripping contributed to the total removal of the four VOCs, the extent of stripping should be the least in Run 7 and the most in Runs 6 and 8 to 13. The data presented in the table follow this trend for three of the four VOCs (except for the vinyl chloride in Runs 6, 7 and 9). However, a quantitative correlation of the extent of stripping cannot be made because the operating conditions were different in each run. For example, at a given air to water flow ratio, when oxidant doses are varied, the extent of oxidation also varies. Therefore, the extent of stripping will be indirectly affected.

Table 4 also presents the Henry's law constants for the four VOCs[11]. By comparing these constants for the VOCs, their volatility is expected to increase from left to right:

1,1-DCA a→a TCE a→a 1,1,1-TCA a→a vinyl chloride

However, a significant removal fraction for 1,1,1-TCA and 1,1-DCA were observed to be due to stripping. Conversely, the extent of stripping was low for vinyl chloride and TCE. This difference in stripping rates is because it is easier to oxidize vinyl chloride and TCE than 1,1-DCA and 1,1,1-TCA because there are double bonds between the carbon atoms in TCE and vinyl chloride. In other words, in the UV/oxidation process, stripping is a significant removal pathway for compounds that are difficult to oxidize.

Performance of the Decompozon Unit

The ozone concentrations in the influent to and the effluent from the Decompozon unit were analyzed in each run. These concentrations are presented on a semi-log plot in Figure 8. The effluent ozone concentrations were low (less than 0.1 ppm) for Runs 1 to 8, approximately 1 ppm in Runs 9 and 10 and greater than 10 ppm in Runs 11, 12 and 13. The high ozone levels (greater than 1 ppm) in the effluent are attributed to the malfunctioning heater in the Decompozon unit. The temperature in the Decompozon unit should have been 140°F for the unit to properly function, whereas the temperature for Runs 11 to 13 was only approximately 80°F. The ozone destruction efficiencies greater than 99.99% were achieved in Runs 1 to 10.

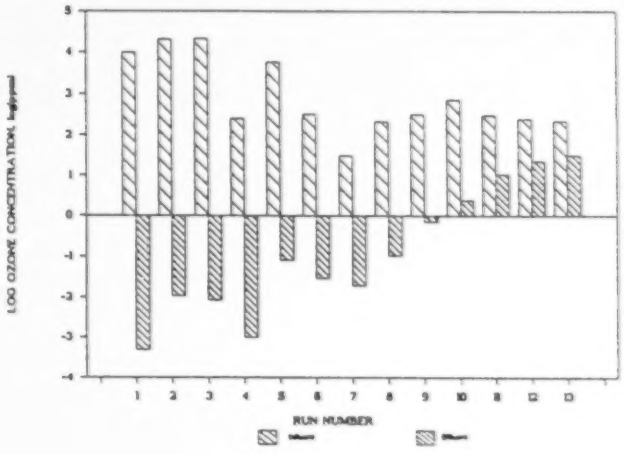


Figure 8
Ozone Concentration in Different Runs

Although the primary function of the Decompozon unit is to remove ozone, the data presented in Table 5 indicate that significant VOC removal occurred when the unit functioned as designed (Runs 1 to 8).

Table 5
VOC Removal in the Decompozon Unit

Run No.	TCE, ppm Influent	TCE, ppm Effluent	1,1-DCA, ppm Influent	1,1-DCA, ppm Effluent	1,1,1-TCA, ppm Influent	1,1,1-TCA, ppm Effluent	Vinyl chloride, ppm Influent	Vinyl chloride, ppm Effluent
1	0.15	<0.15	0.1	<0.1	0.15	<0.1	0.002	<0.002
2	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.070	<0.002
3	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.002	<0.002
4	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.002	<0.002
5	0.15	<0.15	0.2	<0.1	0.1	<0.1	0.150	<0.002
6	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.002	<0.002
7	0.15	<0.15	0.15	<0.1	0.1	<0.1	0.517	<0.002
8	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.041	<0.002
9	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.002	0.061
10	0.225	<0.15	0.15	<0.1	0.1	<0.1	0.064	0.078
11	0.55	0.325	0.25	0.2	0.2	<0.1	0.570	0.189
12	0.15	<0.15	0.2	<0.1	0.1	<0.1	0.271	0.006
13	0.45	<0.15	0.23	<0.1	0.1	<0.1	0.420	0.004

Summary of Results for Noncritical Parameters

In addition to the critical parameters (VOCs), many non-critical parameters also were measured. The non-critical parameters for organics included changes in semi-volatiles, PCBs/pesticides and total organic carbon (TOC); the non-critical parameters for inorganics included changes in pH, conductivity and alkalinity. Temperature, turbidity, residual oxidants and electricity consumption also were measured.

No semi-volatiles or PCBs/pesticides were detected in the influent

or effluent. TOC removal was achieved only at trace levels indicating that complete oxidation of organics to carbon dioxide and water did not occur. However, since no new VOCs were found by GC/MS analysis and GC analysis of the effluent, the oxidation products were not VOCs.

Metals such as iron and manganese were present at low concentrations in the influent and no significant metal removal occurred. No changes in alkalinity and conductivity were observed after the treatment. However, the pH increased by 0.5 to 0.8 units after the treatment. The increase in pH is probably due to the reaction between hydroxyl radicals and bicarbonate ion (the predominant form of alkalinity at the groundwater pH, which is 7.2) in which hydroxyl ions are produced[13].

Turbidity increased by 1 to 4 units after the treatment. This increase may be due to the insignificant amount of metal removal by oxidation and precipitation. The temperature increased by approximately 4 to 5°F after the treatment and was due mainly to the heat from UV lamps. The efficiency of ozone gas transfer to the groundwater was over 95%, with 5% remaining in the reactor off-gas. After the reaction, the residual ozone and hydrogen peroxide concentrations in the effluent usually were less than 0.1 ppm. The average electrical energy consumption to operate the Ultrox system was approximately 11 kwh/h of operation.

CONCLUSIONS

The groundwater treated by the Ultrox system met the discharge standards for disposal into a nearby waterway at the 95% confidence level at a hydraulic retention time of 40 minutes, an influent pH of 7.2 (unadjusted), an ozone dose of 110 mg/L, a hydrogen peroxide dose of 13 mg/L and with all 24 UV lamps operating.

There were no VOCs detected in the air emissions from the treatment unit into the atmosphere.

The ozone destruction unit (Decompozon unit) destroyed reactor off-gas ozone to levels less than 0.1 ppm (OSHA Standards) with destruction efficiencies greater than 99.99%.

The Ultrox system achieved removal efficiencies as high as 90% for total VOCs present in the groundwater at the LB&D site. The removal efficiencies for TCE were greater than 99%. However, the maximum removal efficiencies for 1,1-DCA and 1,1,1-TCA were approximately 65% and 85%, respectively.

The removals of 1,1-DCA and 1,1,1-TCA are due to both chemical oxidation and stripping. Specifically, 12 to 75% of the total removals for 1,1,1-TCA and 5 to 44% of the total removals for 1,1-DCA were due to stripping. However, stripping for TCE and vinyl chloride was observed to be less than 10%. For other VOCs, such as 1,1-dichloroethene, benzene, acetone and 1,1,2,2-tetrachloroethane, stripping was found to be negligible. VOCs present in the gas phase within the reactor at levels of approximately 0.1 to 0.5 ppm were removed to below detection levels in the Decompozon unit.

Based on the GC and GC/MS analyses performed for VOCs, semivolatile organics and PCBs/pesticides, no new compounds were discovered in the treated water. The organics analyzed by GC methods represent less than 2% of the TOC present in the water. Very low TOC removal occurred, a result which implies that partial oxidation of organics took place in the system but not complete conversion to carbon dioxide and water.

The Ultrox system's average electrical energy consumption was approximately 11 kwh/hr of operation.

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